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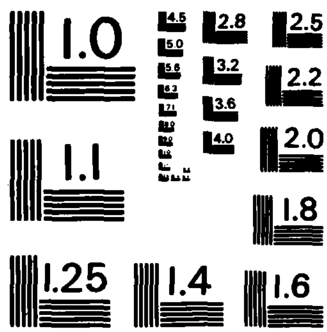

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THE BROADBAND NORMAL MODE MODEL PROTEUS

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This report describes the PROTEUS model, a computer program developed at Applied Research Laboratories, The University of Texas at Austin (ARL:UT), to calculate a broadband set of normal modes for range invariant environments.

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EXECUTIVE SUMMARY

This report describes the PROTEUS model, a computer program developed at Applied Research Laboratories, The University of Texas at Austin (ARL:UT), to calculate a broadband set of normal modes for range invariant environments.

The detection of a low frequency broadband sound source in shallow water has become a significant problem in underwater acoustics. The assessment of the environment's impact on such a detection process requires (in addition to a specification of the source and a choice of detection algorithm) some means of modeling the signal propagation. Ray theory, while an excellent approximation for high frequency or deep water, loses its validity in the present regime where the water may not be many wavelengths deep. A wave theory propagation model such as a normal mode model is needed.

At ranges of interest (≥ 5 water depths) continuous spectrum contributions are nil, and the acoustic field can be constructed solely from the discrete modes. The calculation of a suitable mode set for a given frequency is well understood[1] and computer models exist to do the job. PROTEUS is a multifrequency extension of one such model--ARL:UT's robust single frequency mode model NEMESIS.[2]

I. INTRODUCTION

In 1983 the normal mode model PROTEUS ~~was~~ developed at ARL:UT for use in the analysis of ocean acoustic data. The model and its postprocessors simulate broadband propagation in range invariant environments. A wave theoretic approach was chosen to allow operation at low frequency in shallow water (≤200 Hz, ≤300 m), where ray theory may not be applicable. PROTEUS ~~was~~ based on the original ARL:UT single frequency normal mode model NEMESIS in order to limit software development time while producing a reliable program with a familiar user interface. This report describes the foundations of the PROTEUS ~~model~~ and presents sample output products.

II. OUTLINE OF THE PROBLEM

PROTEUS solves the depth separated wave equation

$$\frac{d^2u_n}{dz^2} + \left\{ \frac{\omega^2}{c(z)^2} - k_n^2 \right\} u_n = 0 \quad , \tag{1}$$

with boundary conditions

$$u_n(0) = 0 \quad , \tag{2}$$

$$\rho_\ell * u_n(H_\ell^-) = \rho_{\ell+1} * u_n(H_\ell^+) \quad , \tag{3}$$

$$\left.\frac{du_n}{dz}\right|_{z=H_\ell^-} = \left.\frac{du_n}{dz}\right|_{z=H_\ell^+} \quad , \tag{4}$$

where

u_n is the eigenfunction (a velocity potential),
k_n is the eigenvalue,
z is the depth,
ω is the (radian) source frequency,
$c(z)$ is the sound speed profile,
ℓ is the environmental layer index
(1 = water, 2 = first sediment layer, ...),
H_ℓ^-, H_ℓ^+ are the depths just above and below the bottom of the ℓth layer ($H_0^+=0$),
ρ_ℓ is the density of the ℓth layer, and
n is the mode number.

The boundary conditions embody the following physical requirements.

(1) The sound field must vanish at the air-water interface (pressure release condition).

(2) The pressure must be continuous.

(3) The vertical component of the fluid velocity must be continuous.

Operation is limited to low frequency (less than 1 kHz), and to range invariant environments. The model assumes that the environment is composed of up to 10 horizontally stratified fluid layers representing the water and the sediment. Within each layer the sound speed may vary with depth, but the density remains constant throughout the layer. Below the fluid layers is a semi-infinite substrate with constant density, sound speed, and shear speed. Sound speeds and densities may be discontinuous at layer boundaries.

III. COMPUTER METHODS

In constructing the model, attention has been focused on the development of analytical capability rather than on the development of new numerical methods. Consequently, the proven methods used in NEMESIS (e.g., parallel shooting with a Numerov integrator) were adopted wherever and whenever possible. The remainder of this section describes the "fixes" that proved necessary for efficient broadband operation.

Speed was an important factor. The necessary broadband products could be generated by separate NEMESIS runs at a series of frequencies, together with an interpolation postprocessor. That approach, however, is too slow. It wastes a great deal of time by making the iterative algorithm start over from scratch at each new frequency. Instead, at each frequency above the lowest one, PROTEUS gets its initial eigenvalue estimate by extrapolating the results from the previous frequency. The estimate for k_n at $\omega+\Delta\omega$ is simply

$$k_n(\omega+\Delta\omega) \simeq k_n(\omega) + \frac{\Delta\omega}{v_n(\omega)} \quad ,$$

where $k_n(\omega)$ and $v_n(\omega)$ are, respectively, the eigenvalue and group velocity found at the previous frequency, ω. For frequency steps of typically $\Delta\omega/2\pi \simeq 10$ Hz, this bootstrap procedure reduces the required iterations and thus the run time by roughly a factor of 10.

Another important consideration was portability of the model. NEMESIS was written in FORTRAN 66 and Control Data Corporation (CDC) assembly language. Had PROTEUS followed this lead, it would be necessary to change the assembly language portions at every non-CDC facility, and probably to convert to the now standard FORTRAN 77. Instead, PROTEUS was implemented entirely in ANSI standard FORTRAN 77. Portability problems should thus be reduced to an absolute minimum.

After speed and portability, the most important design factor was the data storage method. The model generates large output files which must be accessed repeatedly by the postprocessor routines to obtain eigenvalue/eigenfunction information for various frequencies and mode numbers. To make this process as efficient as possible, the data files are direct access files, which can be accessed randomly according to record number. Each is accompanied by a sequential directory file which associates record number with mode number and frequency. To extract data, a postprocessor need only read the correct record numbers from the directory file and then access the data file. This avoids the considerable expense that would be associated with reading all the data from one large sequential file.

IV. SAMPLE OUTPUT

This section contains examples of the graphical outputs of the postprocessors currently available for PROTEUS. All of them pertain to the environment shown in Fig. 1. This figure depicts the sound speed profile in the water and sediment and is labeled with the densities of the water, sediment (a single layer in this example), and substrate, as well as the name of the data file (IND4).

Figures 2, 3, and 4 show the first three modes in 10 Hz increments from 30 to 100 Hz. (They have discontinuities at the sediment interface since they are velocity potentials, rather than pressures.) From these, the user can form qualitative estimates of (1) the amount of vertical movement of the mode maxima with frequency and (2) the degree of mode penetration into the sediment. Figure 5 quantifies the latter. Here, the mode penetration depths (i.e., turning depths) for these modes are shown as a function of frequency.

In Fig. 6, the eigenvalues for the first 30 modes are plotted against frequency. The associated group velocities and resulting mode arrival times at 1 km are plotted in Figs. 7 and 8, respectively.

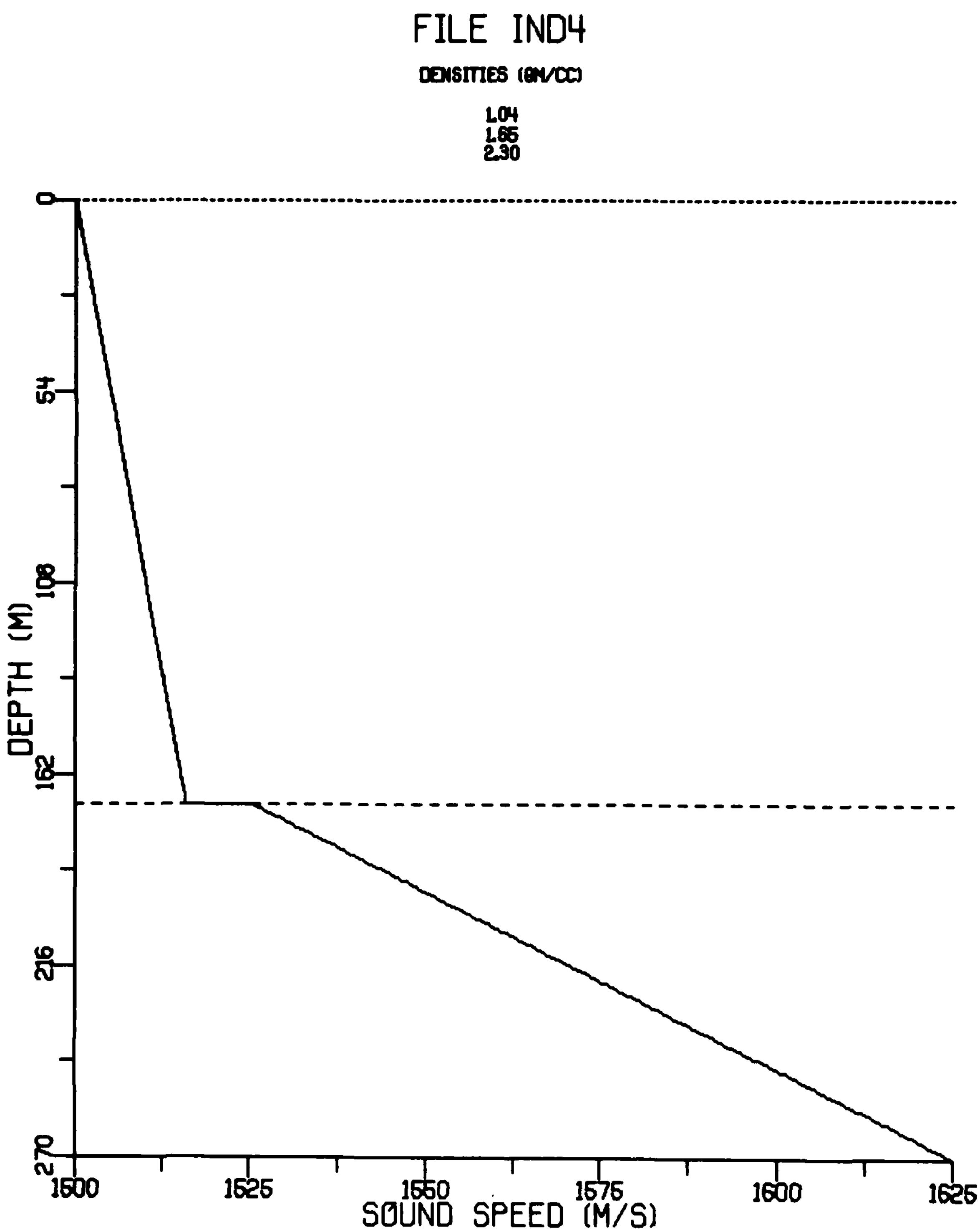

FIGURE 1

SHALLOW WATER ENVIRONMENT SOUND SPEED
PROFILE FOR WATER AND SEDIMENT
(DENSITIES ARE FOR WATER, SEDIMENT, AND SUBSTRATE)

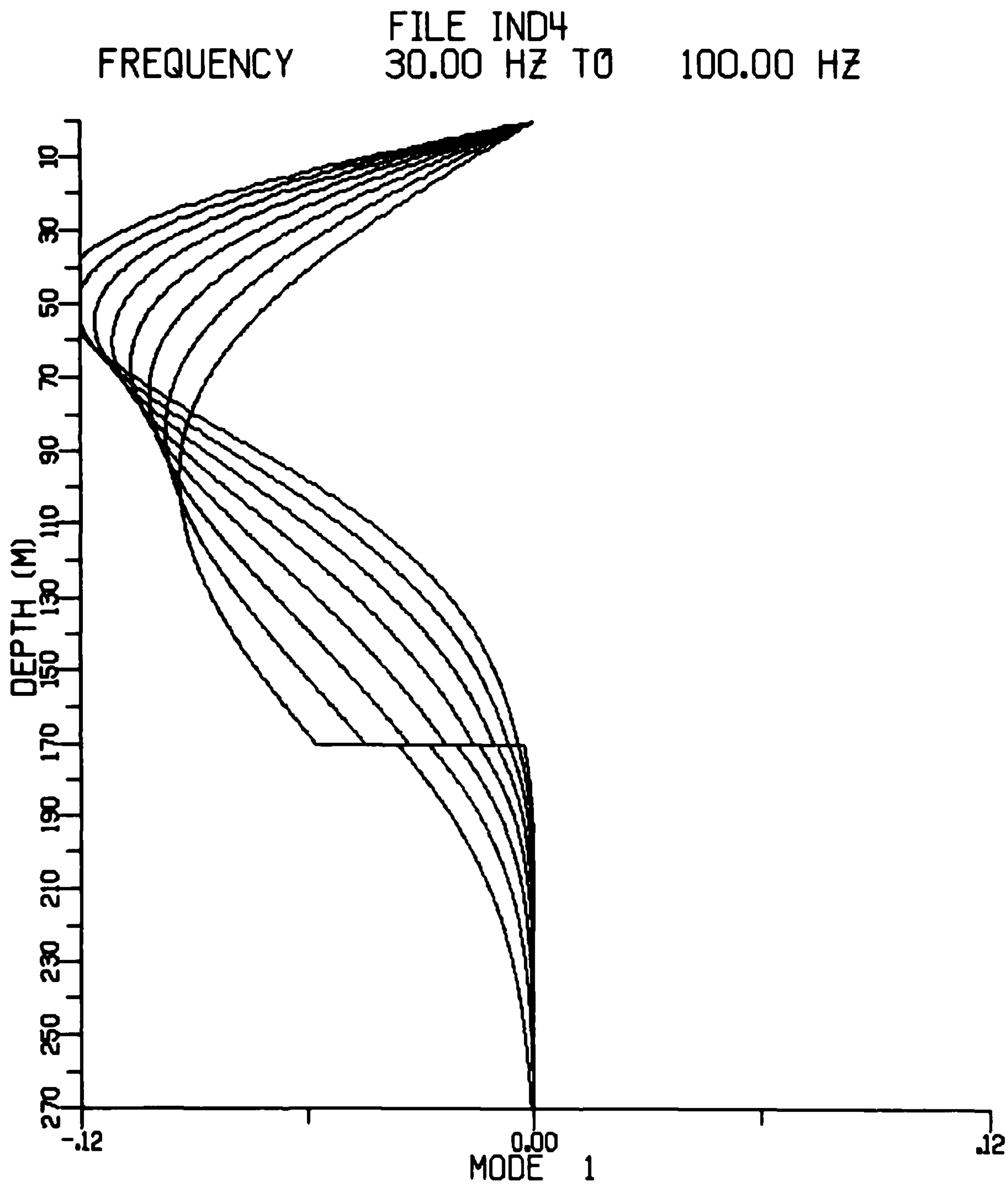

FIGURE 2
MODE 1 AT 30, 40, ..., 100 Hz

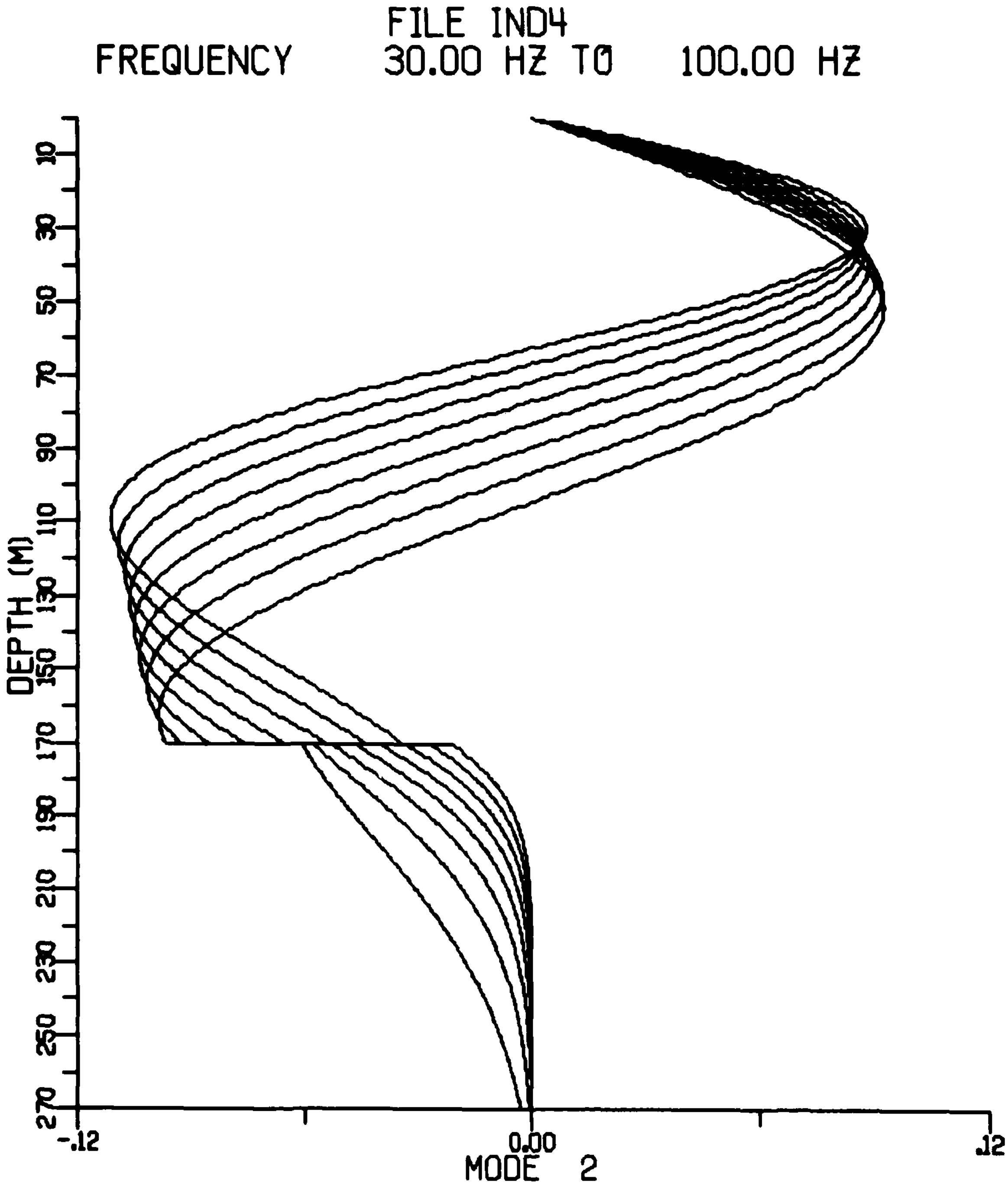

FIGURE 3
MODE 2 AT 30, 40, ..., 100 Hz

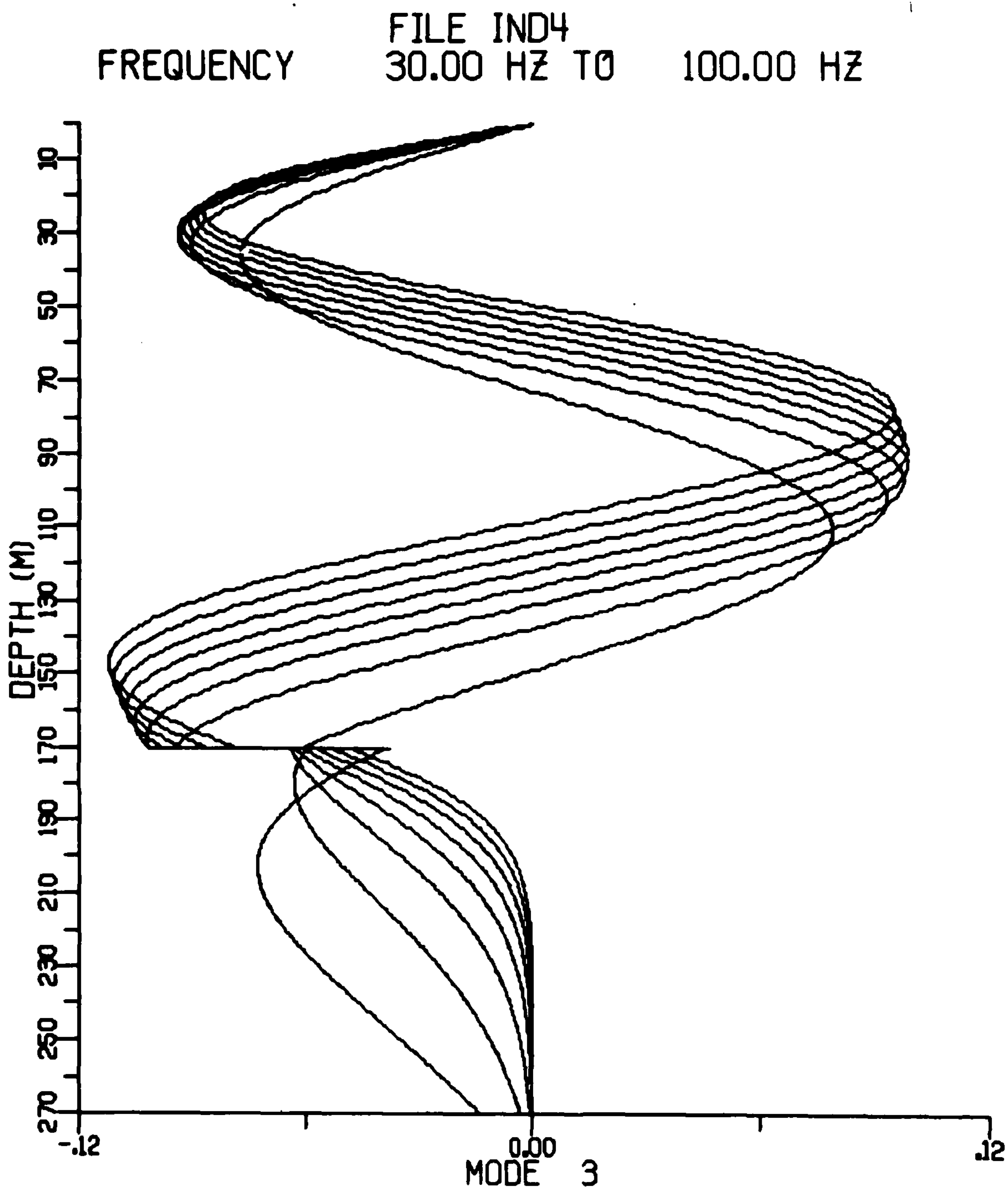

FIGURE 4

MODE 3 AT 30, 40, ..., 100 Hz

INDH

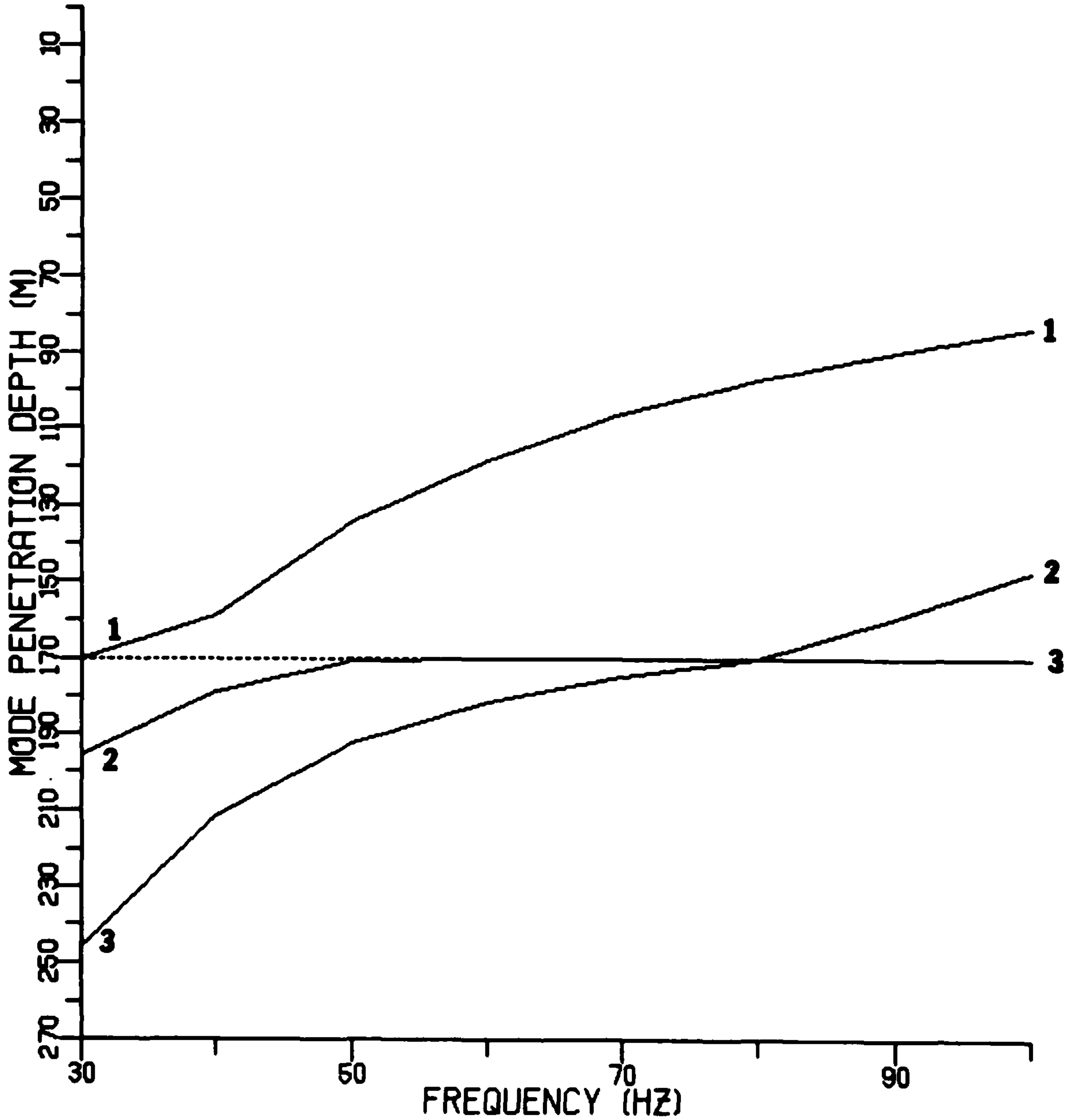

FIGURE 5

MODE PENETRATION DEPTHS FOR
MODES 1, 2, AND 3 AT 30, ..., 100 Hz

IND4

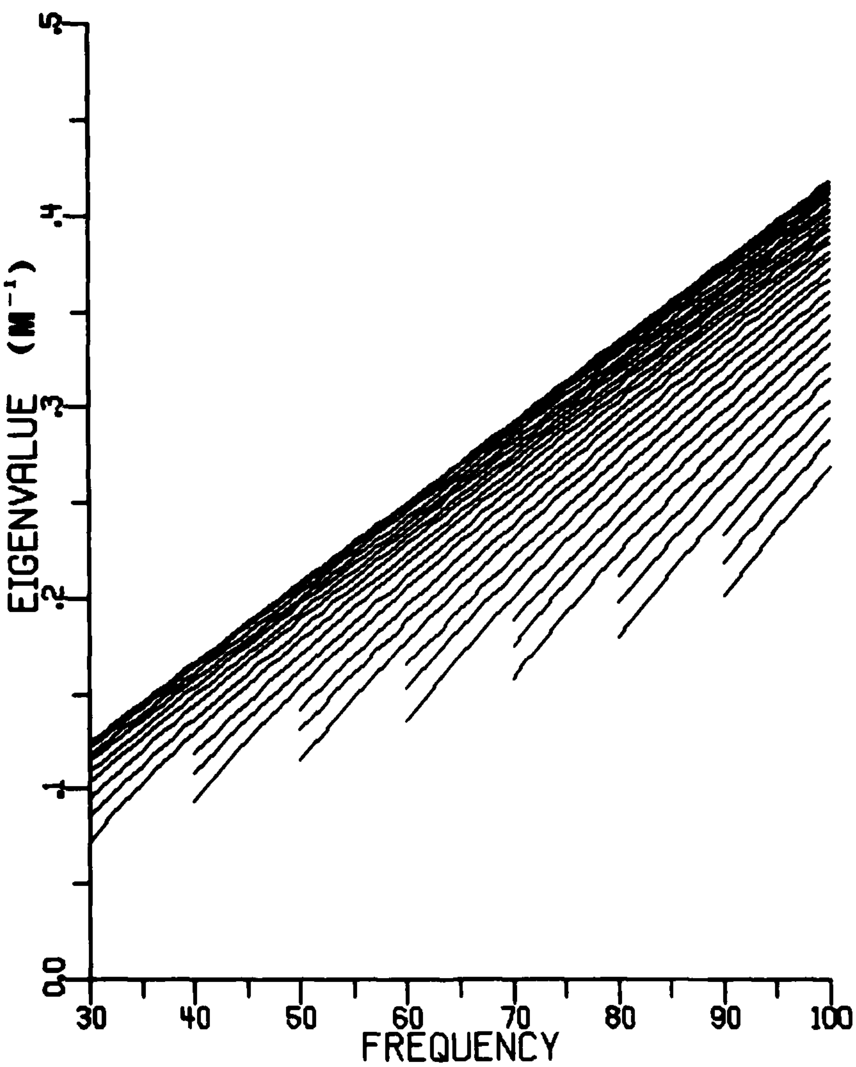

FIGURE 6

EIGENVALUES FOR MODES 1 TO 30 AT 30, ..., 100 Hz

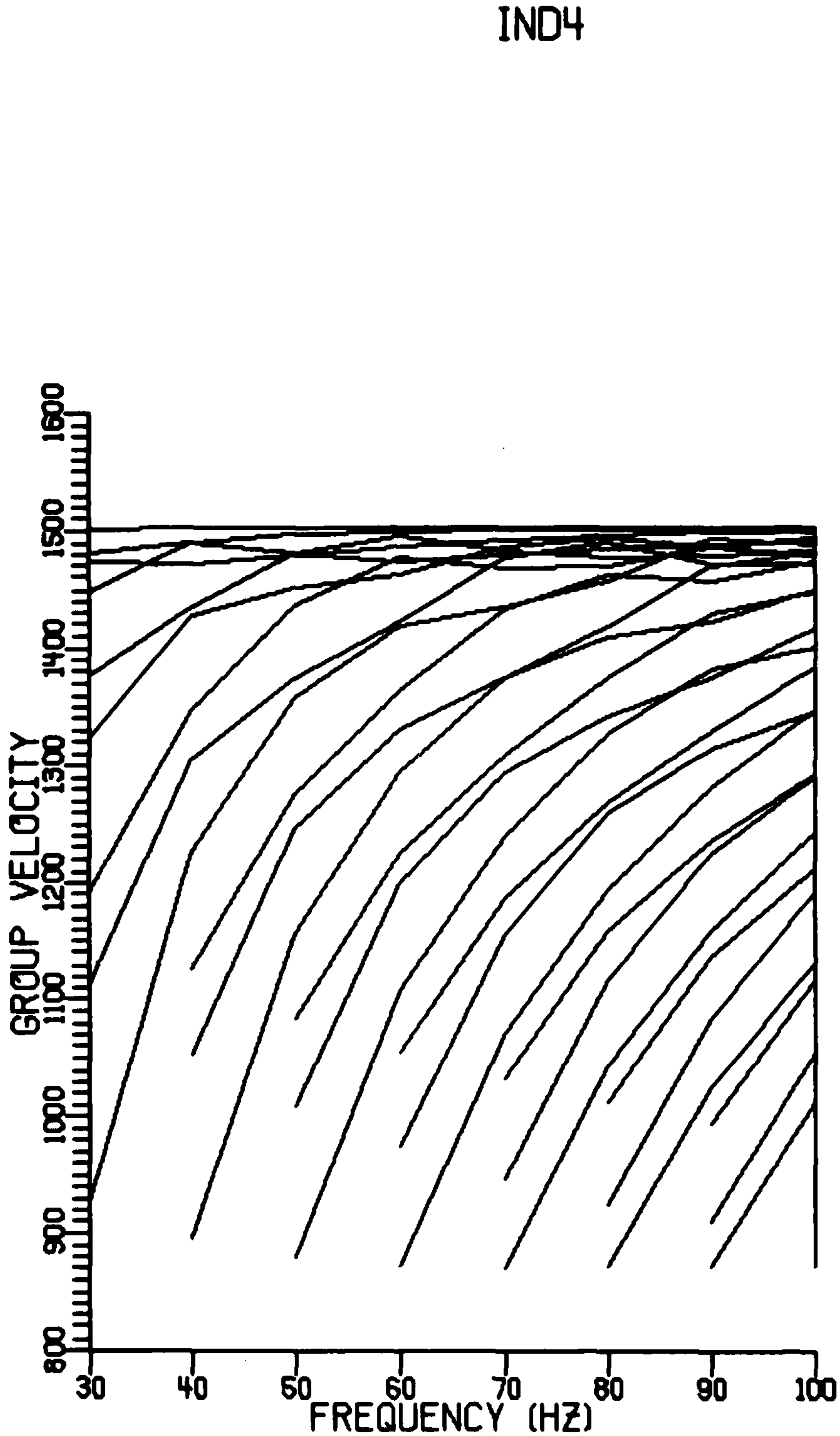

FIGURE 7

GROUP VELOCITIES FOR MODES 1 TO 30 AT 30, ..., 100 Hz

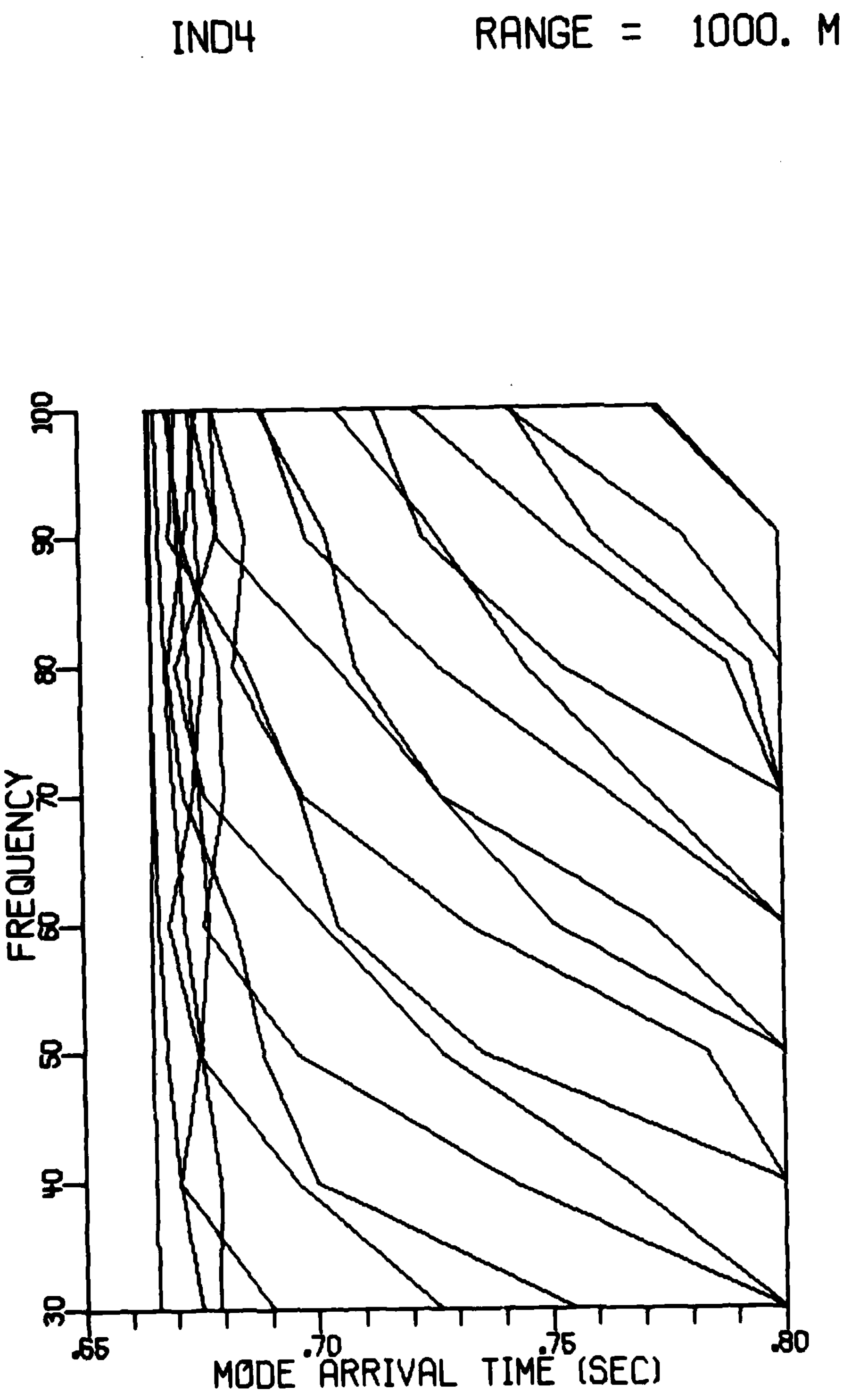

FIGURE 8

MODE ARRIVAL TIMES AT 1 km RANGE FOR MODES 1 TO 30
AT 30, ..., 100 Hz

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2. ARL:UT Technical Report on NEMESIS, in preparation.

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